Potential of monitoring Nitrogen Oxides with satellite instruments

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NO_2 measurements from satellite

Nitrogen oxides ($NO+NO_2=NO_x$) are **important trace gases** in the troposphere, affecting **human health, rain acidity and ozone production**. Spectral measurements from **satellite instruments** like the Global Ozone Monitoring Experiment **GOME** on ERS-2, the SCanning Imaging Absorption SpectroMeter for Atmospheric CHartographY **SCIAMACHY** on ENVISAT, or the Ozone Monitoring Instrument **OMI** on AURA, allow the retrieval of **NO_2 column densities**. By subtracting the estimated stratospheric column and accounting for radiative transfer, **Tropospheric Vertical Column Densities** (TVCDs) are retrieved.

The satellite measurements provide **long time series** with **global coverage**. The resulting TVCDs illustrate the **spatial distribution of tropospheric NO_2** (Fig. 1). Several studies have demonstrated the potential of satellite data to **identify and quantify different sources** of NO_x, for instance continental fossil fuel combustion, ship emissions, biomass burning, soil emissions, and lightning. Furthermore, also the mean lifetime of tropospheric NO_x can be determined. Here we present some **highlights** of recent applications of satellite NO_2 data: the **weekly cycle** of NO_2 from space, the direct observation of **lightning NO_x**, the detection of a **ship track**, and the estimation of the **mean lifetime** of tropospheric NO_x.

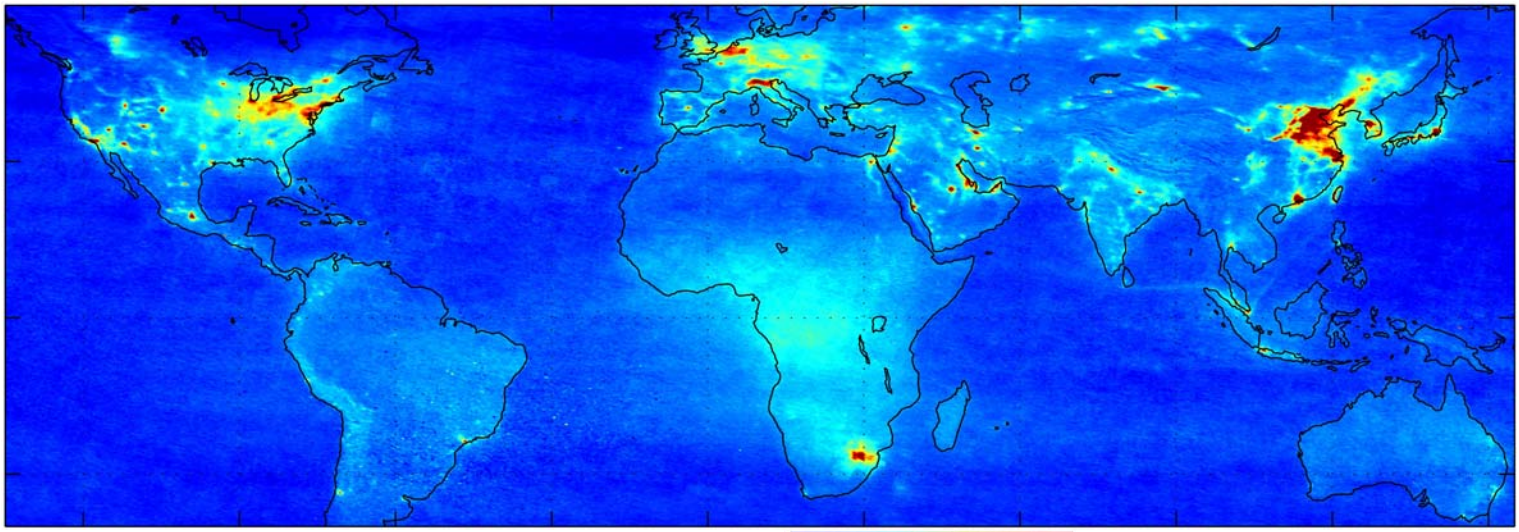


Figure 1: *Mean tropospheric NO_2 VCD from SCIAMACHY (January 2003—June 2004).*

Weekly cycle of tropospheric NO_2

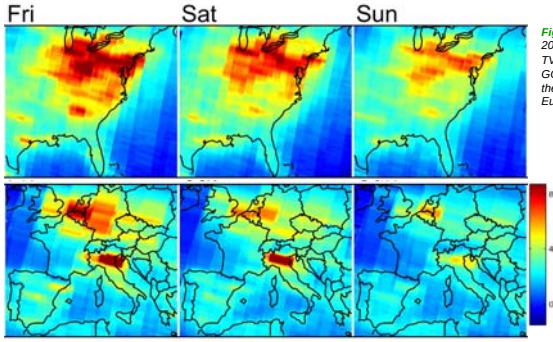
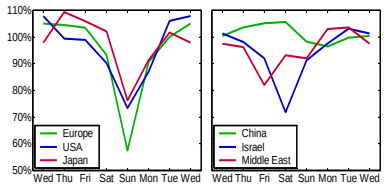


Fig. 2: Six years mean (1996-2001) of tropospheric NO_2 TVCDs (10^{15} molec/cm²) from GOME for Fri, Sat and Sun for the US East Coast (above) and Europe (below).

Fig. 3: Normalized weekly cycles for Europe, the USA, Japan (left) and China, Israel and the Middle East (right).

Since human activity in western countries is governed by a **seven day cycle**, emissions are reduced over weekends. This **weekend reduction** is reflected in GOME NO_2 TVCDs that show a distinct Sunday minimum for the US, Europe and Japan (Fig. 2, 3a) with **local reductions up to 60%**. No weekend reduction is observed for **China**. In the **Middle East**, the minimum is **shifted** (Fig. 3b).

As the different sources of nitrogen oxides like traffic, power plants or industry have different weekly patterns, the detection of a weekly cycle of NO_2 from space helps us to **learn more about the regional influence of the different sources of nitrogen oxides.**



→ *Beirle et al., Weekly cycle of NO_2 by GOME measurements: a signature of anthropogenic sources, ACP 3, 2225-2232, 2003.*

Lightning NO_x

Lightning provides a natural source of nitrogen oxides, dominating the production in the **tropical upper troposphere**, with strong impact on **tropospheric ozone** and the atmosphere's **oxidizing capacity**. Recent estimates of lightning produced NO_x (LNO_x) are of the order of 5 Tg [N] per year with still **high uncertainties** in the range of one order of magnitude.

Here we present **GOME NO_2** measurements **directly over a large convective system** over the Gulf of Mexico. On 30 August 2000, a series of 14 GOME pixels shows largely enhanced TVCDs (Fig. 1a) that have been observed over thick and high clouds (Fig. 1c). Simultaneously, cloud-to-ground flashes are counted by the U.S. National Lightning Detection Network (NLDN™), showing strong lightning activity (Fig. 1b).

The enhanced TVCDs can not be explained by transport of anthropogenic NO_x and must be due to **fresh production of LNO_x**.

A quantitative analysis yields a LNO_x production of 77 (27-230) moles of NO_x, or 1.1 (0.4-3.2) kg [N], per flash.

If **simply extrapolated**, this corresponds to a **global LNO_x** production of **1.5 (0.5-4.5) Tg [N]/yr.**

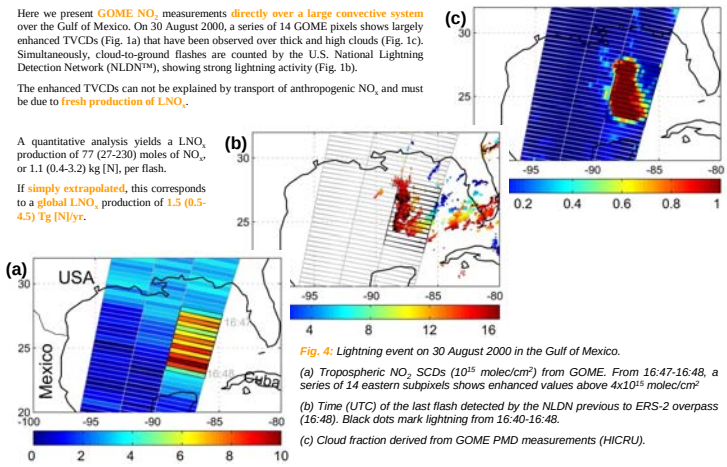


Fig. 4: Lightning event on 30 August 2000 in the Gulf of Mexico.

(a) Tropospheric NO_2 SCDs (10^{15} molec/cm²) from GOME. From 16:47-16:48, a series of 14 eastern subpixels shows enhanced values above $4x10^{15}$ molec/cm²

(b) Time (UTC) of the last flash detected by the NLDN previous to ERS-2 overpass (16:48). Black dots mark lightning from 16:40-16:48.

(c) Cloud fraction derived from GOME PMD measurements (HICRU).

→ *Beirle et al., Estimating the NO_x produced by lightning from GOME and NLDN data, ACPD, 2005.*

Ship emissions

In recent years, the role of **ship emissions** has attracted increasing attention. Recent inventories estimate that they **contribute significantly to anthropogenic emissions** of nitrogen oxides, with a large impact on composition and chemistry of the marine boundary layer. Nevertheless, the number of observational studies is still rather small. Here we present the **first detection of ship tracks in NO_2 maps** derived from satellite data. We have used the congested track connecting Sri Lanka to Indonesia to estimate the corresponding ship emissions of nitrogen oxides to 23 (10-73) Gg [N]/yr.

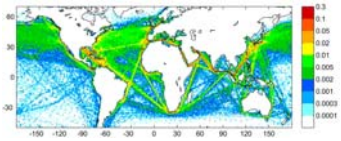


Figure 5: Ship emission inventory (mg [N] per m² and year) using the AMVER distribution of ship reporting frequencies.

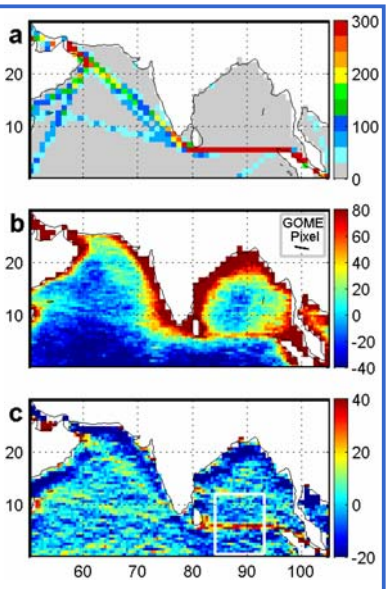


Figure 6: Nitrogen oxide emissions from ships in the Indian ocean.
a) AMVER inventory data (mg [N] per m² and year)
b) NO_2 TVCDs (10^{13} molec/cm²) of cloud free GOME measurements of spring 1996-2001.
c) High-pass filtered NO_2 TVCD. Additionally, the two major tracks west of India emerge. The box (84°-93° E, 0°-12° N) indicates the data used for the quantitative estimate of NO_x emissions from ships.

→ *Beirle et al., Estimate of nitrogen oxide emissions from shipping by satellite remote sensing, Geophys. Res. Lett., 31, L18102, 2004.*

Lifetime of NO_x

The **lifetime** τ of NO_x is a very **important parameter for tropospheric chemistry** in general, and for the quantitative interpretation of satellite based TVCDs of NO_2 in particular. τ controls the **ozone production efficiency**, determines the **area affected by NO_x emissions** via transport, and is needed for the **conversion of TVCDs to NO_x emissions**.
Here we present **two approaches** to **estimate the lifetime** τ of tropospheric NO_x with satellite data:

Lifetime estimatioan I: Downwind decay of NO_2.

The analyzis of the **downwind evolution** of NO_2 plumes holds information on the NO_x lifetime τ.
For constant wind speeds, τ can be derived by an **exponential fit**. This has been successfully applied to estimate the mean lifetime of ship emissions in the ship track connecting India and Indonesia (Figs. 6a, 7), resulting in 2.3 hours in summer and 5.1 hours in winter.
Currently, refined studies are performed for several locations of different latitudes using the Lagrangian particle dispersion model **FLEXPART** driven by highly resolved ECMWF windfield data to simulate the transport of NO_x instead of assuming constant wind speeds.

Lifetime estimation II: Weekly cycle of NO_2

The **weekly cycle** holds information on the lifetime of NO_x: Saturday inherits the weekday pollution from Friday, while pollution on Monday is reduced by the comparably clean Sunday air masses. The longer τ, the higher is the **impact of previous days emissions** on the weekly cycle.
We use a **simple parameterization** of the weekly cycle of NO_2 to estimate τ from a least-squares fit for different regions and seasons.
Fig. 8 shows the resulting weekly cycles for Germany. In summer, Monday TVCDs are similar to those of the other working days, while in winter the Monday levels are below Saturday values. The fitted lifetimes are 6 h and 24 h, respectively.

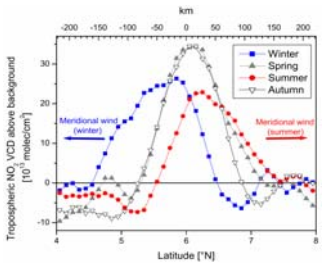


Fig. 7: High-pass filtered NO_2 TVCD, zonally averaged, as function of latitude The asymmetry of the winter and summer sections due to strong meridional winds is used for the lifetime estimation..

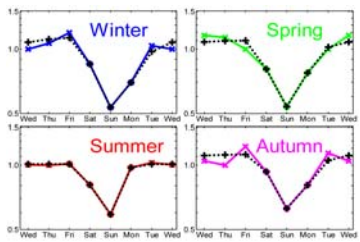


Fig. 8: Normalized weekly cycles for Germany from GOME (colored) and fitted (black).

Further information: **http://satellite.iup.uni-heidelberg.de**

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